

## The character of glaciotectonism

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### Abstract

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Glaciotectonic features are those structures and landforms produced by deformation and dislocation of pre-existing soft bedrock and drift masses as a direct consequence of glacier-ice movement. Some glaciotectonic structures form essentially in-situ; however, most glaciotectonic features involve detachment of a large rock or sediment mass, called a raft, floe, or megablock, and its transportation and deposition by the ice. The main factors in determining whether glaciotectonic structures could develop are: (1) competence of the bedrock relative to glacier ice, (2) distance of megablock transportation, and (3) mode of deposition. Development of glaciotectonic features depends to a large degree on lithology of the affected rocks or sediments. Glaciotectonism does not represent a special or unique process operating within the ice; the same dynamic conditions which cause normal glacial erosion and deposition also create glaciotectonic features in appropriate kinds of bedrock.

### Introduction

The term 'glacial tectonic' was adopted in the 1920's by Slater (1926), who emphasized the glacial origin of structurally deformed hills in several parts of England, Denmark, and Canada. Nowadays, the term is usually shortened to 'glaciotectonic' (American) or 'glacitectonic' (British). Glaciotectonic features are generally understood to be those structures and landforms produced by deformation (folding and faulting) and dislocation of soft bedrock and drift masses as a direct result of glacier-ice movement. Glacial depression and rebound of the crust, collapse of ice-contact drift during stagnant-ice melting, and other structures

not affected by moving ice are usually not considered to be glaciotectonic.

Glaciotectonic features may develop in proglacial, ice-marginal, or subglacial settings affecting materials that were either frozen or thawed at the time of deformation. Some glaciotectonic structures, such as diapiric intrusions (Berthelsen 1974) and glaciodynamic melange (Aber 1979), form essentially in-situ. However, most glaciotectonic features involve detachment of a rock or sediment mass from one site and its transportation to another final resting site.

Glacial *floe*, *raft*, or *megablock* are all terms that have been used for such dislocated large bedrock or drift masses. The distance of transportation may

vary from several metres to many kilometres. In a few extreme cases, glacial rafts have been carried hundreds of kilometres (Ruszczynska-Szenajch 1976). Glacial floes may occur singly in horizontal position, such as the Cretaceous sandstone megablocks in south-central Alberta (Stalker 1976), or may be piled up forming conspicuous ice-shoved hills of various types (Bluemle & Clayton 1984). The most spectacular examples are large, trans-

verse ridges of consolidated bedrock, such as the Cretaceous chalk masses at Møns Klint, Denmark (fig. 1). Ice-thrusted ridges consisting primarily of unconsolidated preglacial Quaternary strata are especially well developed in central and north-eastern portions of the Netherlands (fig. 2).

Durable bedrock, such as crystalline or hard sedimentary rock, is rarely affected by glaciotectionism. These rocks are subjected to glacial

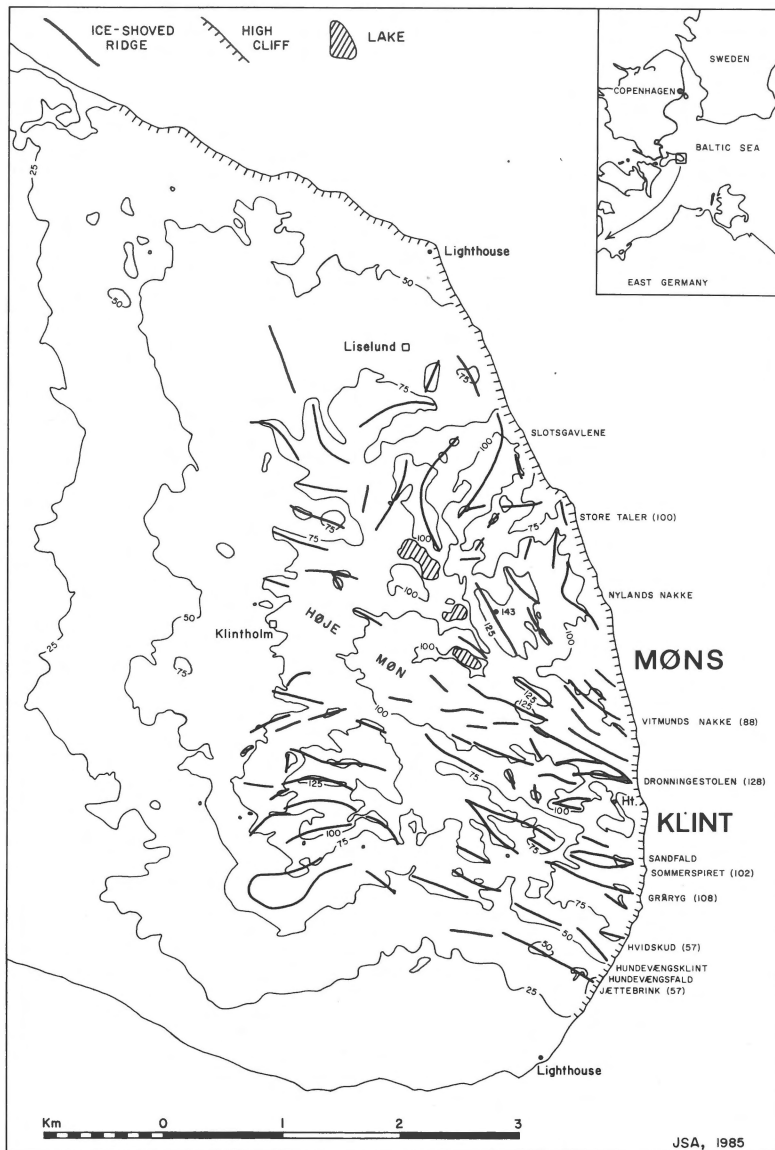


Fig. 1. Topographic map of eastern Møn showing ice-shoved ridges. Individual chalk cliffs and falls are indicated with heights of chalk cliffs given in parentheses. Contour interval = 25 m; Ht. = Hotel. Position of ice-shoved ridges based on interpretation of aerial photographs. Adapted from Aber (1982, fig. 2).

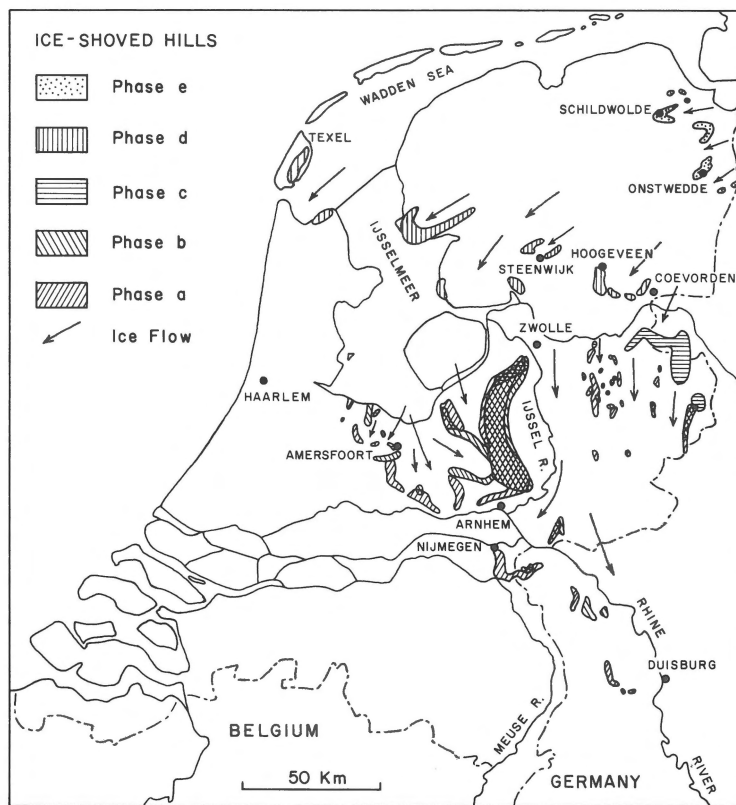


Fig. 2. Ice-pushed ridges of the Netherlands. Five phases (a - oldest, e - youngest) of Saalian ice-pushing are recognized. Some ridges, particularly in central Netherlands, were deformed during more than one phase. Adapted from Ter Wee (1962, figs. 10, 11, 12, 13, 14).

erosion by abrasion, crushing, or plucking (quarrying), and the eroded material is transported by the glacier and eventually deposited from ice or meltwater. Larger clasts of transported rock are called glacial *erratics* or *exotics*. The largest known erratics may weigh several thousand metric tons, and some were transported hundreds of kilometres. Famous examples include the Oregonia (Silurian limestone) erratic of southwestern Ohio (Wolford 1932) and the Okotoks (Precambrian quartzite) erratic south of Calgary, Alberta (Beaty 1975). The only essential difference between these huge erratics and glaciotectionic megablocks is the fact that the erratics are composed of hard, undeformed rock.

What then is the difference between glaciotectionism and normal glacial erosion and deposition? It appears at first that the only difference is the kind of bedrock affected by glaciation. Some geologists view glaciotectionic structures as a form of incom-

plete or partial glacial erosion in soft bedrock. Penetratively deformed (soft) bedrock and glaciodynamic melange can also be classified as a form of glacial deposition (Banham 1977). Ruszczyńska-Szenajch (1980) has considered the seeming paradox of normal glacial erosion affecting only hard bedrock, whereas glaciotectionism is restricted to soft rocks and sediments. She proposed (1980, p. 75) to:

... restrict the term glacial tectonics to the mechanical action of glacial ice on its substratum, and the term glacial erosion to freezing-on processes of substratum material to the glacier sole.

Thus, glaciotectionic structures would be produced as a direct result of stresses imposed on the substratum by ice pressure and movement, whereas glacial erosion (plucking) is dependent on thermal conditions developed at the base of the glacier.

## Detachment of megablocks

There are several possible means by which megablocks or large erratics could be detached from the substratum and made ready for transportation by the ice: (1) beheading of buttes, (2) plucking from lee sides of hills, (3) scooping or lifting from depressions, and (4) thrusting at the ice front (fig. 3). Beheading, plucking, and scooping may occur in any position under the ice, but thrusting happens only at the ice margin where thrust-blocks are squeezed out in front of the glacier (Aber 1982). In all cases, detachment takes place along a pre-existing weak zone, such as: fracture plane, bedding plane, clay or lignite seam, lithologic contrast, or permafrost boundary.

Detachment of megablocks is greatly aided by development of high fluid-pressure within the zone of decollement (Moran 1971; Banham 1975). The physical conditions necessary for overthrusting of large bedrock blocks were elegantly explained by Hubbert & Rubey (1959). They found that as interstitial fluid pressure approaches or equals the unit-area weight of the bedrock, corresponding to flotation of the overburden, the shear stress required to move the block approaches zero. The necessary fluid pressure may be developed when porous, mechanically-weak rocks or sediments of low permeability are subjected to increased compressive stress. This raises the fluid pressure within the rock, expels fluid from the rock, and compacts the rock.

In a glacial context, there are two means of increasing the stress on bedrock and raising the fluid pressure of incompetent strata: (1) gravity-

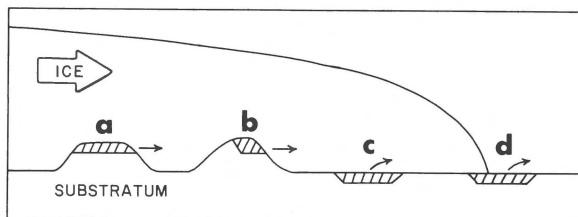


Fig. 3. Mechanisms for glacial detachment of megablocks or large erratics from the substratum. Diagonal lining shows megablocks: a - beheading of butte, b - plucking from lee of hill, c - scooping from depression, and d - thrusting at ice front. Vertical scale exaggerated; a, b, c may occur anywhere under the ice.

loading due to static weight of overriding ice, and (2) horizontal shear due to drag at the bottom of the ice-sheet. The former may exceed 100 bars at the base of glaciers over 1 km thick, but the latter is no more than 1 bar for thawed-bed and 10 bars for frozen-bed glaciers (Weertman 1961).

It is generally agreed that plucking involves a freezing-on process as basal meltwater refreezes in the lower-pressure zone on the lee of an obstacle (Flint 1971). Plucking of large masses can also take place wherever there is a downice transition from thawed bed to frozen bed (Clayton & Moran 1974). Beheading, scooping, and thrusting, however, may be produced by pure mechanical action of the ice affecting either frozen or thawed material. Freezing-on may aid, but is not essential for these mechanisms. Whether detachment is accomplished by thermal or mechanical means or by both, the result is the same: large intact blocks of bedrock or sediment. At this point, there may be no difference between a large erratic of hard rock and a megablock of soft material, nor is there necessarily any difference between blocks detached by thermal and mechanical means. Thus, there is no clear distinction between glaciotectonic detachment and glacial erosion of large blocks, and Ruszczyńska-Szenajch's (1980) restriction of the terms glacial tectonics and erosion would be difficult to apply.

## Transportation of megablocks

Megablocks are generally transported near the base of or in front of the glacier by sliding over the substratum. What happens to any megablock at this stage depends on its competence relative to the enclosing ice and on the distance of movement. Unfrozen megablocks of incompetent sediment will quickly become distorted into featureless blobs due to a strong basal shearing, if transported far. Frozen or more competent sedimentary megablocks may become strongly folded and suffer internal disruption, again due to basal shearing or ice-front pushing, but may still retain traces of primary bedding. Such megablocks with a competence equal to or slightly greater than the ice may undergo considerable transportation and still be

recognizable. Hard bedrock blocks are unlikely to be folded by less competent ice, but may, if well jointed, simply be pulled apart into smaller and smaller fragments with increasing distance of transportation.

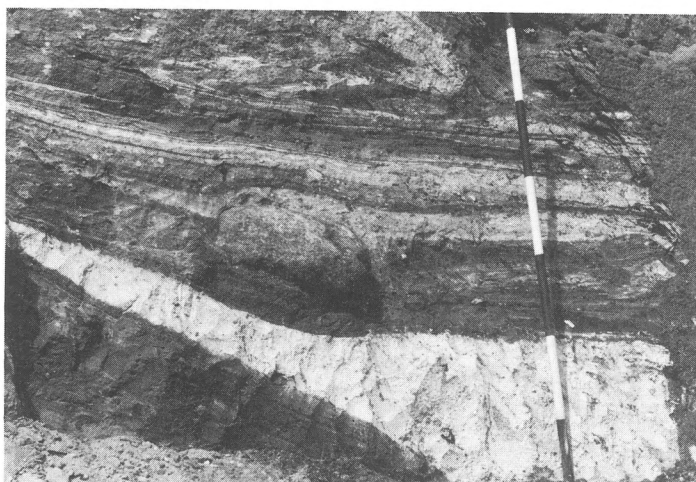
A distinction between normal glacial drift and glaciotectonic material begins to emerge during the transportation stage. Only those megablocks that the ice is capable of deforming, but which are not destroyed, have the potential of forming glaciotectonic structures. Those hard rocks that remain internally undeformed become erratic clasts, and very soft materials will become mixed together with the basal drift carried by the glacier. Deformable megablocks have a limited distance of survival during ice transportation; most were probably not carried farther than a few tens of kilometres. On the other hand, resistant erratics, such as quartzite or granite, may be transported great distances. Thus, megablocks in transit represent deforming rock masses that the ice has not yet been able to break apart or homogenize with the remaining drift.

### Deposition of megablocks

Megablocks are deposited directly from basal or frontal ice by either mechanical lodgement or melting out. Deposition may take place when the

decollement over which the megablock was sliding ceases to operate and a new decollement forms above the megablock allowing ice overriding. Alternatively, the entire ice mass containing the megablock could stagnate and disintegrate. Hard bedrock masses can only be deposited as intact blocks, which may later be subjected to glacial abrasion or crushing, but cannot be deformed. Soft megablocks may also be deposited as relatively intact masses, or may be further deformed and even obliterated during deposition. A soft megablock of roughly the same competence as the enclosing ice may be deformed by the same shear stress which deforms the basal ice. The megablock could be faulted into a series of thin slices, which become stretched out and folded by simple shearing (Berthelsen 1979, fig. 12). If the shear folding incorporates drift with the deformed rock, then glaciodynamic melange is the result (fig. 4). This basal shearing process could eventually destroy any trace of the former megablock.

Megablocks which manage to survive the vicissitudes of glacial transportation and deposition fall into two general categories: (1) single, more or less horizontal rafts, and (2) multiple, stacked or imbricated floes. The single megablocks sometimes have little or no topographic expression, and they may be roughly conformable within local drift stratigraphy. Many single megablocks were probably derived by beheading or plucking from



*Fig. 4.* Photograph of chalk-banded till, or glaciodynamic melange, from Hvideklint, island of Møn, Denmark. Note the stretched, recumbent folds near the top. Scale pole marked in 20-cm stripes.

individual buttes or hills, and so may be scattered over a broad region of glacial deposition. Stacked megablocks, on the other hand, usually form prominent transverse ridges immediately downice from the source depressions, which today often contain bogs, lakes, or seas. Imbricated stacking of megablocks may be produced by scooping or frontal-thrusting, with only a relatively short distance of transportation and with emplacement of relatively intact rock masses. This form of glaciotectonism is mostly associated with ice-margin positions (Gry 1940; Kupsch 1962; Ter Wee 1962; Moran et al. 1980; Aber 1982). Situations intermediate between these two categories also exist.

### Glaciotectonic characteristics

The following characteristics are basic to all glaciotectonic landforms and structures:

(1) The feature must partly or wholly incorporate recognizable masses of pre-existing bedrock. Bedrock is here used in the general sense of any older rock or sediment over which the glacier transgressed. Such rock masses should preserve visibly distinct lithologic and stratigraphic features inherited from the source bedrock. An additional criterion must be applied, because both erratics and megablocks share this attribute.

(2) The bedrock mass must display deformation in the form of folds, faults, sheared zones, diapirs, etc. Such deformations may be internal to a single megablock or may represent the cumulative structures of multiple stacked megablocks that were deformed together. Erratics are intact bedrock blocks that display no such deformation.

The primary factors in determining whether glaciotectonic structures could develop are competence of the bedrock relative to glacier ice, distance of transportation, and mode of deposition. In-situ (autochthonous) deformation may be produced by basal shearing of bedrock whose competence is roughly equal to ice competence or by fluidized flow of incompetent (thawed) material. Allochthonous megablocks may be detached

by various thermal or mechanical manners, and if their competence is not much greater than the ice, they may be deformed during transportation or deposition.

The following example will demonstrate the importance of lithologic control of deformation. Consider ice advancing over a poorly-consolidated sandstone in which scattered hard concretions are cemented. The hard concretions would end up as intact erratic boulders, while other masses of the sandstone could be detached and deformed into megablocks, or the remaining sandstone could simply be eroded bit-by-bit and mixed together with basal drift. Frozen or stronger lithified zones within the sandstone would have better potential for becoming megablocks than would thawed or softer zones. In all cases, the parent bedrock is subjected to the same glaciation, but the results depend on variations in competence of the bedrock.

Thus, the development of glaciotectonic features *does* depend on lithology of the affected rocks or sediments. Glaciotectonism does *not* represent a special or unique process operating within the ice; the same dynamic conditions which cause normal glacial erosion and deposition also create glaciotectonic features in appropriate kinds of bedrock. The manner by which a megablock was detached for ice transportation may be difficult or impossible to determine, and in any case is not a fundamental aspect of glaciotectonism. What happens to the megablock during transportation and deposition determines whether any glaciotectonic features would result.

The recognition of glaciotectonic features based on the two basic characteristics given above should be clear in most situations. There are, however, some cases where the glaciotectonic character of a structure or landform may be difficult to recognize. This is particularly true if the deformed bedrock masses consist mainly of pre-existing drift that is similar to the enclosing drift:

Large-scale block inclusion of drift poses especially serious problems, because it is usually very difficult to detect. Large-scale block inclusion has probably played a major role in the formation of many if not most of the classical end

moraines of midwestern United States. (Moran 1971, p. 137).

Large glacial erratics, such as the Okotoks quartzite, may be disrupted by pulling apart along joints. This is not considered to be a glaciotectionic phenomenon, because the joints are assumed to be inherited from the parent rock and not a product of glacial stresses. Likewise, blocks of frozen sediment may be picked up and redeposited by the glacier. Such blocks, termed 'frigites' by Barbour (1913), may be perfectly preserved. Frigites that display evidence of internal deformation are glaciotectionic, whereas intact frigites are merely glacial erratics. In all cases, the key is recognition of pre-existing rock or sediment bodies that were deformed as a direct result of glacier-ice movement.

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